Optimized Control of an Induction Motor Drive fed by PWM Voltage Source Inverter and active filter

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Abstract: - This paper deals with a new optimized control of induction motor in adjustable speed drives. This control method uses both active filtering techniques and optimized PWM waveforms. The optimization of PWM waveforms is effective with power supply and active filter too. In addition, the following study take account of hardware constraints in order to limit cost. *IMACS/IEEE CSCC'99 Proceedings,* Pages:3711-3716

Key-Words: - Optimized PWM, Induction motor, Active filter, Voltage Source Inverter, Harmonic.

1 Introduction

The improvements of the power semiconductor technology and processor performances allow to ensure an efficient control of induction motors in variable speed drives. For medium and large power applications, the possibilities of the semiconductor components are still limited. Consequently, hard constraints have to be respected to ensure a non-destructive control of the switching devices like GTO (Gate Turn Off) thyristors for instance. The switching frequency may be significantly limited and a minimum conduction time has to be respected. In these conditions, the classical modulation methods produce voltage and currents harmonics. Then, pulsating torques and high peak currents appear and the efficiency of the system is reduced.

The use of optimized PWM waveforms becomes in this case very interesting or even necessary to improve the harmonic content of the voltages and phase currents. These PWM waveforms are computed at first by applying mathematical criterion minimization or low order harmonics cancellation.

There is an other possibility to improve harmonic content, this new method uses active filtering technique [1]. Besides, the active filter can work in complement with optimization method.

In this paper are presented : optimized command principle, system configuration, calculation of optimized control for the entire system, results and conclusion.

2 Optimized command principle

The power converter act as an imperfect sinusoidal voltage supply because of undesirable harmonics. Therefore we take an interest in reducing these harmonics by filtering. The control of variable speed induction motor drives impose adjustable frequency supply, consequently a passive filter is not efficient. Active filtering principle is to correct voltage supply (Vconv) imperfections with help of auxiliary voltage supply (Vfilt) as shown Fig.1. The object of Vfilt is to produce the same harmonics as in Vconv, injected in opposition, in order to obtain a load voltage with the less harmonics as possible. In our case, the load is a three-phase induction motor which act as a current supply, then a series active filter is used rather than shunt one [2].

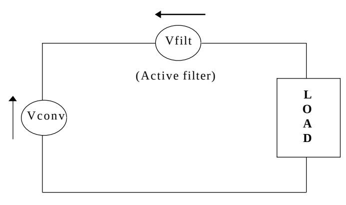

Fig.1 : Simplified injection schema

Two PWM method types are used to sweep all the frequency area of induction motor running. The first is sinusoidal asynchronous PWM for low frequency, to start the motor, and the second is optimized PWM for all the other frequencies. It is about this last one we speak in what follows. To achieve the best filtering performances, the optimized command takes account of power supply and filter as a whole.

3 Filtering process

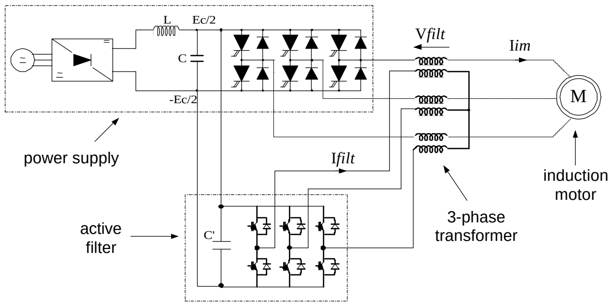

Fig.2 : system configuration

3.1 System configuration

The complete system includes the power supply, the active filter and a transformer to optimize the command of induction motor. The power supply consist of a rectifier, a filter and a PWM inverter. The active filter is a three-phase inverter with a transformer to inject Vfilt. Vfilt is created by this inverter to be the nearest of harmonic content of Vconv. The transformer is very useful for several reasons. It permit the use, for the active filter, of a three-phase inverter with six transistors instead of three single-phase inverter with four transistors. Utilization of the continuous voltage supply (Ec) is possible thanks to galvanic insulation. In addition, selection of transformer ratio allows to adapt voltage and current in active filter.

3.2 Active filter sizing constraints

Generally speaking, the aim is to limit at the most the filter sizing constraints without deteriorate the effectiveness of the filter. So, the choice of electric variables and frequency in the filter is very important. It allows to have a low cost filter with little power dissipation to ensure an efficient filtering. For example, voltage amplitude (Vfilt) must be high enough to ensure good injection, but not too much high because of the raise of inverter cost with current amplitude [3]. As a matter of fact, the more Vfilt will be low the more inverter current will be low too, thanks to the transformer. Inverter current is divided by transformer ratio. In addition, a low voltage Vfilt avoid to submit motor winding to too much high voltage. The power dissipation in filter semiconductors will be all the smaller since the following values will be small :

- the current in the filter
- the continuous voltage of the filter
- the switching frequency

The continuous voltage supply Ec is chosen to feed the filter. The power inverter switch are sized to accept this voltage, we take care that the filter switch too. The current in the filter is decreased at the most by choosing a suitable transformer ratio m. This current is called I_{filt} and the motor current is called I_{im} :

$$I_{filt} = \frac{I_{im}}{m} \qquad (1)$$

Then, the maximum amplitude of Vfilt due to transformer connection is given by the following relation :

$$V_{filt} = \frac{2E_c}{3m} \qquad (2)$$

This value restrict the injection possibility of high amplitude harmonic.

4 Optimized control computation

4.1 Constraints on PWM waves

Some constraints are issued from the semi-conductor technology and the power dissipation abilities of the snubber circuits. They become very important and penalizing in the medium and large power area considered here, essentially when GTO thyristors have to be used. They are applied both to voltage source inverter and active filter. These constraints essentially result in a large minimum pulse width (up to 150 µs) due to semi-conductor dynamic features, security delay time applied to each rising edge of gate control, and discharge delay of the snubber circuits.

From these constraints results some rules applied to power converter and filter PWM waves. These rules define the limits of the commutation frequency (F_{com}), and the minimum pulse width (T_{min}).

For the power inverter we chose the following example :

$270\text{ Hz} < F_{com} < 540\text{ Hz}$

$T_{min} = 150\ \mu s$

For active filter, we have :

$270\text{ Hz} < F_{com} < 1000\text{ Hz}$

$T_{min} = 10\ \mu s$

These rules allow us to make a choice of the PWM waves to use, depending on the rotor frequency of the induction motor. Actually, it is possible to define availability frequency bands for PWM waves depending on the number of commutations included in the PWM wave fundamental period. In fact PWM waves are chosen symmetric and consequently are defined by only the commutations included in the first quarter of the fundamental period.

Inferior commutation frequency limit (270 Hz) is chosen to avoid PWM waves with bad spectral features. Available frequency bands for power inverter PWM waves are represented Fig.3.

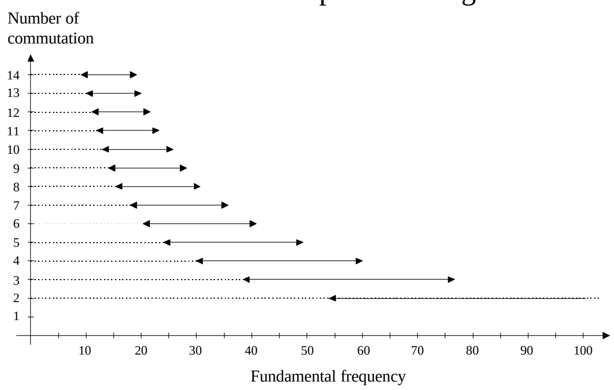

Fig.3 : Available frequency bands of PWM waves.

For some frequencies, several PWM waves are available. The choice between the solutions is realized to get the better spectral features as explained in the following sections, and to minimize the commutation frequencies and then the losses in the converters [4].

Another constraint in the choice of the PWM waves, is the motor control principle. It defines the amplitude of the fundamental voltage applied to the motor, depending on its fundamental frequency. Therefore, that allows to keep a constant magnetic flux in order to have a constant maximum torque, up to the rating frequency F_0 of the motor. For greater frequencies, the amplitude of the fundamental voltage is kept constant to rating voltage V_0 to protect motor windings as described Fig.4.

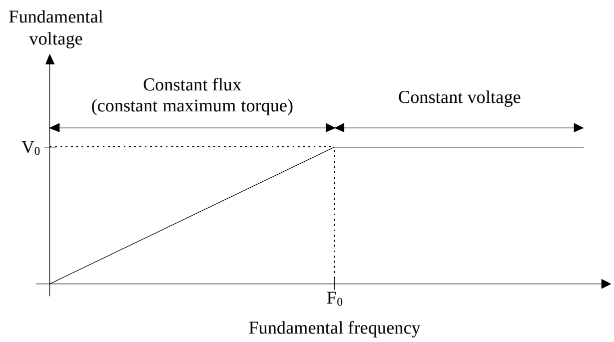

Fig.4 : Induction motor control law.

Therefore, this control law is applied by adapting the modulation rate of the power inverter PWM waves, which adjust the fundamental amplitude of the voltage.

4.2 Optimization criteria

The control of the power PWM inverter and the active filter are radically dependent. The performances of the motor control are improved by optimization of spectral features of voltages and currents [5]. This is realized by the associated control of the power PWM inverter and the active filter.

Among the optimization methods which lead to reduce harmonic current, torque ripples, peak current, and rotor losses, two are used here [6].

First of all, low rank harmonic elimination can be used when the number of commutation in a fundamental period is important. It allows to get first non zero harmonics to sufficiently high frequencies to be naturally filtered by the induction machine. The PWM waves which allow to eliminate harmonics are processes from the expression of the voltage harmonics V_k :

$$V_k = \frac{2E_c}{k\pi} \cdot \left(1 + 2\sum_{i=1}^{C} (-1)^{i+1} \cos(k\alpha_i) \right) \quad (3)$$

with Ec : DC voltage feeding the power inverter
k : rank of the harmonic
C : number of commutations in $[0,\pi/2]$
α_i : commutation values in $[0,\pi/2]$

Then, for a PWM wave with C commutations, a system with C equations is constituted. Then, it is possible to eliminate C-1 harmonics and fix the fundamental amplitude to respect the induction motor control law shown Fig.4. Consequently, that results in a PWM wave for which the low current harmonics are eliminated due to the following relation :

$$I_k = \frac{V_k}{kL\omega} \quad (4)$$

with L : harmonic model of the induction motor

The limit of this method appears when not eliminated current harmonics have low frequency and high amplitude. In this case, better results are provided if the harmonic current I_{harm} is minimized :

$$I_{harm} = \frac{I_{eff}}{I_{eff\,1}} - 1 \quad (5)$$

with I_{eff} : RMS value of the current
I_{eff1} : RMS value of the fundamental current

This is realized by minimization of the following current harmonic distortion rate :

$$t = \frac{1}{V_1}\sqrt{\sum_{k=5,7,11,...}^{Nh}\left(\frac{V_k}{k}\right)^2} \qquad (6)$$

where Nh defines the last harmonic to take into account depending on the filtering ability of the induction motor and then the inductance L.

4.3 Computation method

The computation of the optimized control defines the PWM waves which control the power inverter and the active filter. The method takes into account the previously enumerated constraints, the adapted minimization criterion and the associated action of the power inverter and the active filter. It consists in the three following subsection.

4.3.1 Power inverter PWM waves computation

First of all, the minimization criterion is chosen. For sufficiently high commutation frequencies, the harmonic elimination is more adapted. It allows to eliminate harmonic up to high frequencies. Then, the harmonic current is efficiently reduced. PWM waves are computed by resolution of the non-linear equation system built with V_1, V_{k1}, V_{k2}, ..., $V_{k(C-1)}$, where C is chosen from the available frequency bands described Fig.3. The harmonic ranks k_1, k_2, ..., $k_{(C-1)}$ are chosen odd due to the symmetrical features of the PWM waves, and not multiple of three due to the three-phased connection.

For low commutation frequencies, as in the example given previously ($F_{com} < 540$ Hz), the minimization of the current harmonic distortion rate τ is more adapted. The PWM wave commutations are computed with a numerical method using conjugated gradient algorithm. The method results in a global reduction of the low frequency harmonics.

4.3.2 Harmonic extraction

To build a criterion for computation of the active filter PWM waves, it is necessary to extract the harmonic content of the power inverter PWM waves previously computed.

In the case of the harmonic elimination, the computation of the voltage harmonics leads to the following result :

$V_1 = V(F)$ issued from the control law
$V_{k1} = V_5 = 0$
$V_{k2} = V_7 = 0$
.
.
$V_{k(C-1)} = 0$ (7)
$V_{kC} \neq 0$
$V_{k(C+1)} \neq 0$
.
.
$V_{kmax} \neq 0$

where kmax is the last harmonic rank witch can be eliminated or reduced by the active filter. It depends on the commutation number of the filter PWM wave which is chosen in accordance with the maximum commutation frequency.

For the current distortion rate minimization, the voltage harmonics are not eliminated and have different values :

$V_1 = V(F)$ issued from the control law
$V_{k1} = V_5 \neq 0$
$V_{k2} = V_7 \neq 0$
. (8)
.
.
$V_{Nh} \neq 0$

where Nh is define in the current distortion rate τ.

4.3.3 Active filter PWM waves computation

Then, it is possible to define computation methods of the filter PWM waves, to have the maximum filtering efficiency of the active filter. These methods depend on the optimization criterion previously chosen.

For harmonic elimination, it is possible to eliminate or reduce remaining harmonics V_{kC}, $V_{k(C+1)}$, ..., up to the order of the new equation system which is the number of commutations of the active filter PWM wave. This equation system is defined by the voltage harmonic amplitudes which must be generated by the active filter PWM waves. It is built as following :

$V'_1 = 0$ (it produces no fundamental)
$V'_{k1} = V_5 = 0$
$V'_{k2} = V_7 = 0$
.
.
$V'_{k(C-1)} = 0$ (9)
$V'_{kC} = V_{kC}$
$V_{k(C+1)} = V_{k(C+1)}$
.
.
$V'_{kC'} = V_{kmax}$

where C' is the commutation number of the active filter PWM wave. V_{kC} to V_{kmax} can be completely compensated only if their amplitude is sufficiently low to be created by the active filter. If it is not the case, these harmonics are only reduced. Then, the filter generates the maximum harmonic amplitude.

For current distortion rate minimization, the active filter PWM waves are computed to minimize the residual current distortion rate directly issued from the extracted harmonics (V_{k1} to V_{Nh}). It consists in minimization of the following criterion :

$$t1 = \sqrt{\sum_{k=5,7,11,\ldots}^{Nh} \left(\frac{V_k' - V_k}{k} \right)^2} \qquad (10)$$

Therefore, the PWM waves witch results of the minimization of this criterion leads to apply to the induction motor voltages which produce the minimum harmonic current, and then minimum motor losses and torque ripples.

It is important to note that the computations presented here take into account the transformer ratio, to produce harmonic amplitude V_k' in the power circuit.

5 Results

The following examples illustrate the results issued from harmonic elimination and current distortion rate minimization. The very hard constraints mentioned in section 4.2 are applied to the PWM waves, and the transformer ratio is m = 5. The PWM waves are computed for the rating frequency of 50 Hz and rating torque of a 60 kW test induction motor.

5.1 Harmonic elimination

The PWM waves are computed as previously explained. The power inverter PWM wave have C = 4 commutations, and then a commutation frequency of F_{com} = 450 Hz. It allows to eliminate the ranks 5, 7 and 11 of voltage harmonics. Fig.5 illustrates the phase current and its spectrum when the power inverter is used alone, without active filter.

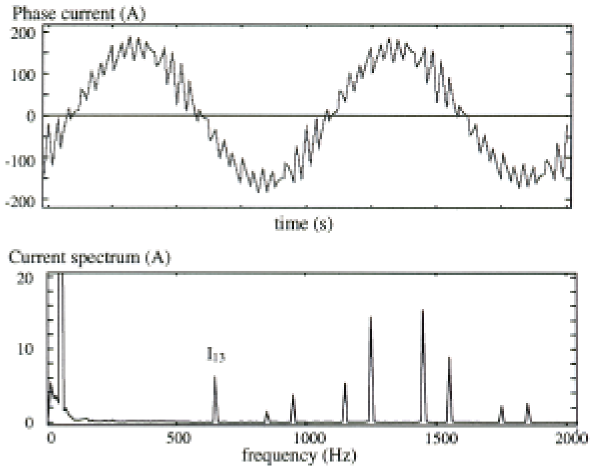

Fig.5 : Harmonic elimination without active filter.

The chosen active filter PWM wave frequency is of 850 Hz. That allows to compute a PWM wave with C' = 8 commutations, to eliminate the ranks 13, 17, 19 and 23 of voltage harmonics. Fig.6 illustrates the corresponding results.

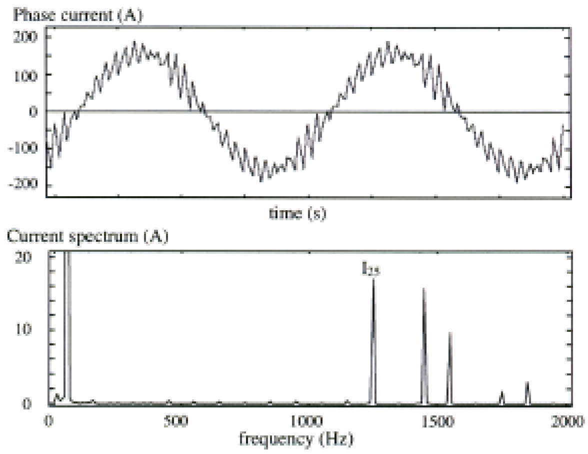

Fig.6 : Harmonic elimination with active filter.

Active filter allows to extend the insufficient performances of the power PWM inverter. However, it remains significant current harmonics down to 1250 Hz, because of the inability to reduce them by the minimization method. Furthermore, the induction motor is not able to filter these remaining harmonics at these low frequencies. The harmonic elimination provides good results, but for this example, the filtering action seems necessary up to about 2kHz. Consequently, this method should be used for greater commutation frequency.

5.2 Current distortion rate minimization

First of all, the power inverter PWM wave is computed to minimize this criterion τ. As previously, the commutation frequency is C = 4 for the power inverter and C' = 8 for the active filter. Fig.7 illustrates the phase current and its spectrum without active filter.

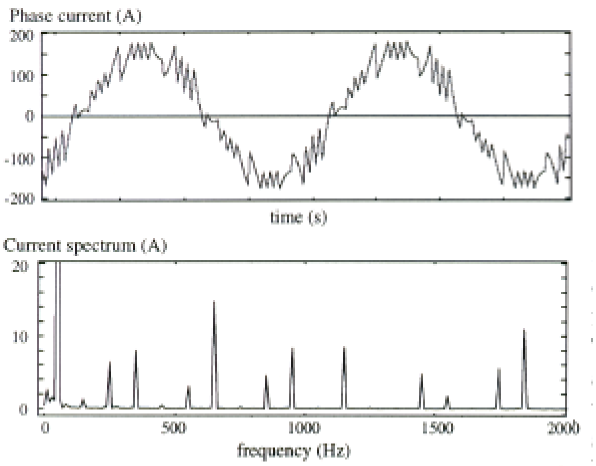

Fig.7 : Current distortion rate minimization without active filter.

The current distortion rate of the power inverter PWM wave is $\tau = 0.0147\%$, taking into account harmonics of which the frequency is inferior to 2 kHz.

Then, the active filter PWM wave is computed according to the minimization of the criterion $\tau 1$ to filter harmonics up to 2kHz. Fig.8 illustrates corresponding results.

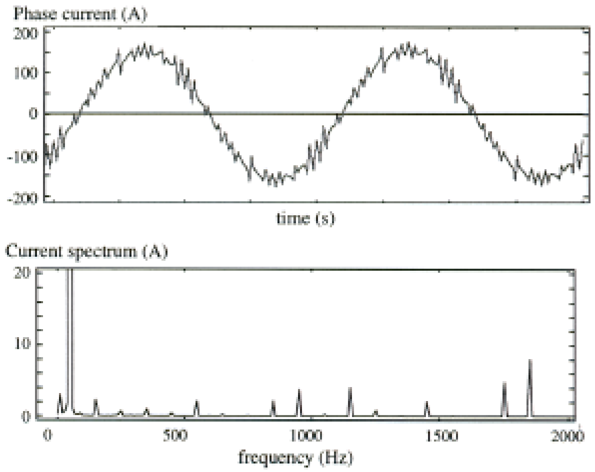

Fig.8 : Current distortion rate minimization with active filter.

The current distortion rate applied to the induction motor become then $\tau = 0.00648\%$. Consequently, the active filter is able to efficiently reduce it. Furthermore, none high amplitude current harmonics are remaining.

6 Conclusion

The computation methods presented in this paper allow to investigate the possible improvements of the induction motor control, provided by the association of a power PWM inverter and a series active filter. The used computation algorithms are developed knowing the power inverter and active filter features, and the motor drive requirements. The PWM waves which control the active filter allow to have a significant improvement, compared to the classic induction motor control realized with a single PWM inverter without active filter. Furthermore, the properties of the optimized PWM waves, allow to get these good results with low active filter commutation frequency. Then, the sizing constraints are efficiently reduced to have the minimum development cost of the active filter.

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